Multi-decadal trends in body size of Puget Sound Chinook Salmon: Analysis of data from the Tengu Derby, a culturally unique fishery

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Abstract

In Pacific salmon, downward trends in size and abundance have been reported for species and stocks for over 40 years, but the patterns are inconsistent among regions and species. Interpretation of these trends is complicated by many possible contributing factors, including short time series, data comprising a mix of stocks, and varying gear types. Here, we present data on the mass of individual Chinook Salmon, *Oncorhynchus tshawytscha*, caught in the winter from 1946 to 2019 in central Puget Sound, Washington by participants in what may be the longest running salmon derby in North America, the Tengu Derby. In this annual recreational fishing competition, established by Japanese-Americans immediately after release from internment camps at the end of World War II, participants follow strict gear, area, and methods regulations, and catch almost exclusively salmon originating from and remaining in Puget Sound. Records revealed an overall decline in fish mass over the decades with a high degree of variability throughout the time series. Specifically, resident Chinook Salmon exhibited several shifts, including a decrease in size from a high in the 1950s to a low around 1980, followed by an increase to another high around 1990, and then a decline over the most recent 30 years. These size trends of residents differed from those of Puget Sound Chinook Salmon as a whole. We infer that the resident salmon experienced ecological conditions affecting their growth that were distinct from those of salmon feeding along the Pacific Ocean in the same periods. These distinct trends in size of Chinook Salmon from common origins indicate that the different migration patterns of salmon within stocks must be considered in the analysis and interpretation of body size trends, and also patterns of survival.

Introduction

Long-term trends in size and age at maturity of fishes have been the subject of interest for many decades, as they may reflect natural changes in environmental conditions ([Cox and Hinch 1997](#_ENREF_9); [Rogers et al. 2011](#_ENREF_47)), density dependence ([Millner and Whiting 1996](#_ENREF_27); [Pyper and Peterman 1999](#_ENREF_36)), fishery management ([Richards and Rago 1999](#_ENREF_42)), fishery induced evolution ([Sharpe and Hendry 2009](#_ENREF_52); [Swain et al. 2007](#_ENREF_57)), and other processes or combinations of processes ([Edeline et al. 2007](#_ENREF_10)). For example, scientists have investigated long-term trends (typically declines) in body size and age at maturity in Atlantic Salmon, *Salmo salar* ([Gardner 1976](#_ENREF_12); [Summers 1995](#_ENREF_56)), using data from commercial fisheries ([Shearer 1990](#_ENREF_53)) and recreational fisheries, recorded by governmental bodies ([Bal et al. 2017](#_ENREF_3)), angling clubs ([Bielak and Power 1986](#_ENREF_4)), privately held fisheries ([Quinn et al. 2006](#_ENREF_40)), or newspapers ([Valiente et al. 2011](#_ENREF_60)).

As with Atlantic Salmon, there is also a long history of interest in trends in Pacific salmon (*Oncorhynchus* spp.) body size, with reports of decreases in many species, regions, and periods of record ([Bigler et al. 1996](#_ENREF_5); [Lewis et al. 2015](#_ENREF_24); [Oke et al. 2020](#_ENREF_31); [Ricker 1981](#_ENREF_44); [Ricker 1995](#_ENREF_45)). As outlined by Ricker (1980) and echoed in subsequent reviews of size trends, many factors can cause genuine or apparent changes over decades, especially in Chinook Salmon, O*. tshawytscha*, owing to its diverse life history and migration patterns. Catch data may include shifting proportions of immature and maturing fish of multiple ages, hence different sizes; or fishing may occur at different times of the year, affecting average size of fish still growing at sea. Smolts produced in hatcheries are often larger than wild smolts, and smolt size affects the duration of marine residence ([Scheuerell 2005](#_ENREF_50); [Tattam et al. 2015](#_ENREF_58)). Hatchery production of Chinook Salmon and Coho Salmon, *O. kisutch*, increased very gradually from about 1900 – 1950 but then accelerated upward in the US Pacific Northwest region, with later increases in British Columbia and Alaska ([Mahnken et al. 1998](#_ENREF_26)). Salmon growth is also affected by oceanographic conditions, competition, and the quantity and quality of prey ([Claiborne et al. 2021](#_ENREF_8); [Helle et al. 2007](#_ENREF_15); [Siegel et al. 2017](#_ENREF_55); [Wells et al. 2008](#_ENREF_64)), all of which have changed over the past decades, and growth rate at sea affects age at maturity ([Parker and Larkin 1959](#_ENREF_34); [Siegel et al. 2017](#_ENREF_55)). Fisheries themselves can be size selective ([Todd and Larkin 1971](#_ENREF_59)), shifting the overall size distribution, or that inferred from a particular fishery ([Kendall and Quinn 2011](#_ENREF_22)). These and other factors affecting the size of salmon are not mutually exclusive, making it difficult to explain the many declines (and some increases) in size and age (see Quinn (2018) for a discussion and review of these factors).

Many data sets examined for patterns of body size in Pacific salmon come from commercial fisheries targeting the most numerous species: Sockeye (*O. nerka*), Chum (*O. keta*), and Pink (*O. gorbuscha*) Salmon. However, Chinook and Coho Salmon are also commonly caught by anglers in coastal marine waters and rivers. Recreational fisheries can complicate analysis of size trends because they may differ in places and times of the year from commercial fisheries, and the lack of centralized processing means that data on size may not be recorded. However, when used with appropriate caution, recreational fisheries can also be a source of data to complement data from commercial fisheries and recoveries at spawning grounds and hatcheries. For example, [Fagen (1988](#_ENREF_11)) examined data from recreational fishing derbies for Chinook Salmon in southeastern Alaska from the 1940s to 1980s, and reported significant declines in the largest fish in two of the four derbies. Interpretation of these data was complicated by the factors noted by Ricker (1980), especially because southeastern Alaska is a feeding area for wild and hatchery Chinook Salmon originating from a range of locations ([Healey and Groot 1987](#_ENREF_14); [Weitkamp 2012](#_ENREF_61); [Weitkamp 2009](#_ENREF_62)). Indeed, [Ricker (1980](#_ENREF_43)) concluded that analysis of size trend data and causes is especially complicated for Chinook Salmon. They vary greatly in age at maturity and size at age within and among populations ([Roni and Quinn 1995](#_ENREF_49)), in marine distribution patterns and timing of entry into fresh water for spawning ([Quinn 2018](#_ENREF_37); [Riddell et al. 2018](#_ENREF_46)), and are fished over a protracted period of the year using a variety of commercial and recreational gear types. Here we consider yet another issue: possible size differences resulting from differential migration within populations.

Recent analysis of trends in survival, abundance, and body size of Chinook Salmon in Puget Sound, Washington, based on commercial purse seine fishery data, revealed a decline in average body mass from 1970 through 2015 ([Losee et al. 2019](#_ENREF_25)). However, these salmon would have differed in feeding locations at sea. Specifically, some might have migrated to the coastal ocean whereas others remained in Puget Sound as so-called “residents.” Such resident Chinook and Coho Salmon are smaller than those that migrate to the coast ([Jensen 1948](#_ENREF_19); [Milne 1950](#_ENREF_28); [Pressey 1953](#_ENREF_35)), complicating interpretation of catch data if the proportion of residents is not constant or if their trends differ from those of the conspecifics feeding along the coast. Here we present data on the size of resident Chinook Salmon (see details below on this migratory variant), caught in the winter in central Puget Sound in a culturally unique recreational fishery with consistent methods held annually since 1946. Trends in these data, specific to resident Chinook Salmon originating in Puget Sound, were examined and compared with those of the species caught in Puget Sound as a whole using non-size-selective commercial purse seines ([Losee et al. 2019](#_ENREF_25)). Our first goal was to use the data to determine the long-term trends in the body size of resident Chinook Salmon, and we then determined whether these trends differed from those of Puget Sound Chinook Salmon as a whole (including residents and salmon caught in Puget Sound that had fed along the coast). In so doing, we highlight the value of recreational fisheries data in general for examining life history trends, and this unique fishery.

Methods

Resident Chinook Salmon

It has long been known that Chinook and coho Salmon occur throughout the year in Puget Sound and other inland marine waters ([Jordan and Evermann 1896](#_ENREF_20)), though many other salmon enter these waters as smolts and then migrate to the coastal ocean, feed there, and pass through the inland marine waters on their homeward migration ([Haw et al. 1967](#_ENREF_13); [Pressey 1953](#_ENREF_35)). The resident salmon are fully anadromous but exhibit differential migration ([Quinn 2021](#_ENREF_38)), remaining in the general vicinity of their natal rivers for much of their period of marine life ([Arostegui et al. 2017](#_ENREF_1); [Chamberlin et al. 2011](#_ENREF_6); [Chamberlin and Quinn 2014](#_ENREF_7); [Kagley et al. 2017](#_ENREF_21)). In the winter and spring, these resident Chinook are subject to capture before they mature and spawn the following fall, or thereafter. Analysis of coded wire tagging (CWT) data indicated that Chinook Salmon caught in Marine Area 10 (central Puget Sound, including the location where the derby occurs that produced the data examined here) were almost exclusively from Puget Sound. Specifically, 90.2% of CWT recovered from Chinook Salmon from October through April (the resident period) in central Puget Sound between 1973 and 2018 originated from Puget Sound (WDFW data, average of annual values). Consistent with this analysis, [Shelton et al. (2019](#_ENREF_54)) examined CWT data from the west coast of North America and concluded, “Virtually all fish estimated to be present in the Salish Sea (Puget Sound, Strait of Georgia) originated there, indicating few Chinook Salmon from the outer coast migrate into the Salish Sea.” Consequently, it is appropriate to consider the fish caught in the winter as having originated from Puget Sound rivers and hatcheries.

The Tengu Salmon Derby

The history and origins of the derby that provided the data for our analyses are described on a monument plaque at the current weigh-in station in West Seattle:

“The Tengu Club of Seattle, formed in the 1930s by Japanese Americans, held its first Tengu Blackmouth Salmon Fun Derby in 1946. Arguably the longest continually running salmon derby in North America, it continues to be held each winter in Elliott Bay. Club members, returning from wartime internment camps, were denied entry into local salmon derbies so they organized the first Tengu Derby in December of 1946. More than 170 people, including about a dozen non-Japanese, fished in the first four Sundays-long competitions. The technique of ‘mooching[[1]](#footnote-1)’ was invented in Elliott Bay by these fishers, who perfected a way to entice salmon by working bait in an up-and-down motion while drifting. This method proved to be so effective that non-Japanese would “mooch” herring from them. The Tengu Club recognized the historical significance of mooching and adheres to this ‘purist’ way of salmon fishing to this day. The name ‘Tengu’ is from Japanese folklore that describes mythical creatures that were mischievous braggarts. Their long noses are symbolic of exaggerating the truth, which is typical of fish stories.”

In the decades that followed, participants in the Tengu Derby continued to use the same technique (e.g., no artificial lures and no trolling with downriggers) and in precisely the same small, well-defined area east of a line between Alki Point and Fourmile Rock (Fig. 1). Each year the club’s Board of Directors determines the specific dates but fishing typically occurs on Sundays in late October, November, and December. Dates and other details are posted annually and registration provides a record of the number of participants. Fish are brought to a central weighing station rather than being self-reported, and thus the data on fish mass (recorded in pounds but converted to kg) can be taken as very accurate.

Each year the mass of each fish was determined but permanent records were only retained for the top five. These data were the focus of our analysis, but the numbers of Chinook salmon over 10 pounds and over 5 pounds were also recorded, and we present these in graphical form for comparison. The total number of Chinook Salmon caught was also recorded each year but changes in regulations over the decades complicate analyses of the count data. Specifically, fish were retained and counted in early decades that would now have to be released and so not counted. For the present analysis we used the average mass of the top five fish from 1946 - 2017, omitting two years (2010 and 2013) when fewer than five Chinook Salmon were recorded, and 2015 when fishing was closed. In 2018 and 2019, fewer than five salmon were caught so the averages were not included. The trends were compared to annual mean body mass of Chinook Salmon caught in Puget Sound commercial purse seine fisheries (chosen because of their lack of size-selectivity) from 1970 – 2014 ([Losee et al. 2019](#_ENREF_25))and updated through 2019 (WDFW, unpublished data). Consistent with Losee et al. (2019), we divided the total number landed in Washington State and Treaty Indian Tribal commercial catches by the total landed weight annually.

Statistical models

We modeled the sizes of fish caught in the Tengu Derby and WDFW surveys using univariate and multivariate state-space models ([Auger-Méthé et al. 2021](#_ENREF_2)). These models consist of two parts: 1) a state model that describes the changes in the true but unknown size of fish; and 2) an observation model that relates the observed time series of fish sizes to the true state. Each of the component models varied subtly, depending on the underlying hypothesis about how the two sources of data were related. Here we wanted to evaluate 1) if there was any evidence for a systematic change in fish size over time; and 2) whether changes in the size of salmon caught in the derby over time were like those fish caught in commercial purse seines. For objective (1), we fit models to the two different time periods mentioned above; models in objective (2) were based solely upon the later period (1970 – 2014).

Beginning with the state model, we modeled changes in fish size using a random walk, for which the change in size over time was assumed to be either biased or unbiased, indicating whether the changes in fish size over time were random or generally trending upward/downward. Specifically, the model takes the form

(1)

where *xi,t* is the natural logarithm of fish size from source *i* in year *t*, *ui* is the bias term for source *i*, and *wi,t* is a residual process error for source *i* in year *t*, such that *wi,t* ~ N(0, *q*). Setting *ui* = 0 gives an unbiased random walk.

The observation model treats the measured masses of adult salmon each year as samples from the distribution of true sizes in the population. Specifically, the model is

(2)

where *yj,t* is the natural logarithm of observed fish mass (kg) from source *j* in year *t*, *aj* is on offset term for source *j*, and *vj,t* is a residual sampling error for source *j* in year *t*, such that *vj,t* ~ N(0, *r*).

When *i* = *j* = *1*, both the state and observation models are univariate and the subscript *i* in equations (1) and (2) can be ignored, as we did when examining the entire time series from the Tengu Derby. When *i* = *j* = 2, the Tengu and WDFW data are assumed to be samples from their own unique populations. For this case, we write equations (1) and (2) in matrix notation where *T* and *W* indicate Tengu Derby and WDFW, respectively, and

(3)

. (4)

As with equation (1), setting the vector yields an unbiased random walk.

When each set of observed masses is assumed to be a sample from the same population, *i* = 1, *j* = 2, and

(5)

. (6)

Setting *u* = 0 in equation (5) results in an unbiased random walk.

In equations (3), (4), and (6), the error vectors are distributed as a multivariate normal. In all those cases, we assumed that the errors were independent, but not identically distributed, such that the covariance matrices had a different variance term in each of the elements of the diagonal, and 0’s in the off-diagonals.

We compared the data support for each of the six state-space models using the corrected form of Akaike’s Information Criterion (AICc, Table 1). All models were fit using version 3.11.3 of the MARSS package ([Holmes et al. 2020](#_ENREF_16)) for the R statistical software ([RCoreTeam 2020](#_ENREF_41)). All the data and code necessary to reproduce our results can be found online at <https://github.com/mdscheuerell/tengu>.

Results

The Tengu Derby data indicated that body size was initially high in the late 1940s and 1950s, declined to a low in about 1980, rose to another peak about as high as the first peak around 1990, and then declined steadily to a current size below the earlier low. These patterns were evident in our primary metric, the average mass of the five largest salmon (Fig. 2), and also in the maximum size each year, and the numbers caught exceeding 5 and 10 pounds (Fig. 3), with peaks occurring in the middle of the time series in the early 1990’s. Given these large shifts in fish mass over time, it was perhaps expected that we did not find any data support for a model that included a consistent bias in size over the entire time period; the AICc for the biased random walk was ~0.6 units higher than that for the unbiased random walk (Table 1).

During the period from 1970 to 2014, the mean fish mass of fish from commercial fisheries appeared to generally decrease, but we found no data support for a decreasing bias in the mass of fish caught in purse seines or the Tengu Derby, as both models with bias terms had AICc values about 1 unit greater than their corresponding models without bias terms (Table 1). Furthermore, temporal patterns in fish mass from the Tengu Derby did not generally match those from the purse seine fishery, despite some similarities from the late 1980s to the late 1990s (Fig. 4); models with two unique states had AICc values that were about 35 units less than the models with only one shared state.

Discussion

The data from the Tengu Derby showed a decline in average mass of the five largest fish (also evident in the maximum mass, and the numbers caught per angler over 5 and 10 pounds each year), from the first records in the mid-late 1940s to a low about 1980. This initial decline mirrored that reported by [Ricker (1981](#_ENREF_44)) for several regions along the British Columbia coast. Subsequent investigations in British Columbia reported an increase in Chinook salmon average mass from that low period to a high around 1990-2000 ([Bigler et al. 1996](#_ENREF_5)), followed by another decline ([Jeffrey et al. 2017](#_ENREF_18)). These patterns approximated those seen in the Tengu Derby data, but they may not reflect common underlying causes. Importantly, we found a lack of alignment between the Puget Sound data from commercial purse seine fisheries targeting migratory adults and those from the derby. Interestingly, data from four regions of Alaska showed downward trends in mean mass of Chinook Salmon from about 1970 – 2000 ([Helle et al. 2007](#_ENREF_15)), thus more similar to the Puget Sound purse seine fishery data than the data from British Columbia reported by [Jeffrey et al. (2017](#_ENREF_18)).

Changes in average size may result from differences in growth rate and shifts in the population’s age composition ([Bigler et al. 1996](#_ENREF_5); [Lewis et al. 2015](#_ENREF_24); [Ohlberger et al. 2018](#_ENREF_30)). Indeed, declines in overall size recently reported for Alaskan Chinook, Coho, Chum, and Sockeye salmon were attributed primarily to reductions in age at maturity rather than size at age ([Oke et al. 2020](#_ENREF_31)). The specific causal mechanisms and factors controlling these changes in age and size remain uncertain, in part because 1) growth and age at maturity are complex inter-related traits, 2) the data typically include varying proportions of populations that differ in size and age, and 3) there are many environmental influences ([Oke et al. 2020](#_ENREF_31); [Ricker 1980](#_ENREF_43)). As with other salmon species, the number of years Chinook Salmon spend at sea is typically inversely related to smolt size ([Quinn 2018](#_ENREF_37); [Scheuerell 2005](#_ENREF_50); [Tattam et al. 2015](#_ENREF_58)) and initial growth rate ([Siegel et al. 2017](#_ENREF_55)). Salmon produced in hatcheries are commonly larger at release than wild conspecifics, and thus younger at maturity ([Norris et al. 2000](#_ENREF_29)). The proportion of hatchery origin Chinook Salmon caught in Puget Sound has increased considerably over the past decades, from < 40% in 1968 and 1969 to an average of 64% in the 1970s, 74% in the 1980s, 79% in the 1990, 82% in the 2000s, and 87% from 2010 – 2015 ([Losee et al. 2019](#_ENREF_25)), complicating interpretation of size trends.

Puget Sound and the entire Salish Sea have undergone many changes over the past decades in physical and ecological attributes ([Quinn and Losee 2022](#_ENREF_39)), and we did not try to ascribe the observed changes in Chinook Salmon mass to specific causes. However, data such as these on the resident component, over such a long period, are unique and especially valuable. Salish Sea resident salmon are smaller than those feeding along the Pacific Ocean coast ([Milne 1950](#_ENREF_28); [Pressey 1953](#_ENREF_35); [Rohde et al. 2014](#_ENREF_48)), thus changes in the proportions of residents and migrants could strongly affect mean body size, depending on where and when the sampling took place. Indeed, the proportion of Chinook Salmon remaining as residents in Puget Sound has decreased over the period covered by the Tengu Derby data ([Quinn and Losee 2022](#_ENREF_39)). The lack of correspondence between the Tengu Derby and purse seining data presented here spanning more than four decades, and the decreasing resident component in the populations, illustrates yet another important complexity in the analysis of temporal trends in salmon body size. That is, the differential migration patterns observed in several species, and especially Chinook and Coho salmon ([Quinn 2021](#_ENREF_38); [Quinn and Losee 2022](#_ENREF_39)) can cause differences in vulnerability to fisheries of contingents that migrate to different areas ([Sharma and Quinn 2012](#_ENREF_51)). If those migratory contingents also differ in size, then the resulting data can be biased, depending on where and when the fish were sampled.

Finally, it is increasingly clear that declines in abundance of Atlantic and Pacific salmon are strongly influenced by survival rates at ([Olmos et al. 2019](#_ENREF_32); [Welch et al. 2021](#_ENREF_63)). However, as exemplified by Atlantic Salmon from the Bay of Fundy, Canada, considerable variation in survival rates can occur among spatially proximate populations ([Pardo et al. 2021](#_ENREF_33)). Some of this variation in survival may be related to the proportions of populations adopting resident or migratory behavior patterns ([Lacroix 2013](#_ENREF_23)), and migratory patterns also affect growth rates ([Hubley et al. 2008](#_ENREF_17)). Thus our results highlight the need to better understand where different genetic groups of salmon go over their entire marine life histories, as these pathways likely affect their growth, as shown here, and also their survival to adult return.

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Table 1. Differences in AICc values between univariate models fit to the full time period and multivariate models fit to the late period only. Bias indicates whether a bias term was included in the random walk model. States and Observations indicate the number of underlying states and time series of observations, respectively.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Time period | Bias | States (*i*) | Observations (*j*) | ΔAICc |
| Full | Yes | 1 | 1 | 0.0 |
|  | No | 1 | 1 | 0.6 |
|  |  |  |  |  |
| Late | Yes | 2 | 2 | 0.0 |
|  | No | 2 | 2 | 1.2 |
|  | Yes | 1 | 2 | 34.6 |
|  | No | 1 | 2 | 35.3 |

Figure 1. Map of Puget Sound, Washington, with an insert showing the location of the Tengu Blackmouth Derby.

Map

Description automatically generated

Figure 2. Time series of the mean mass of the five largest Chinook Salmon caught in the Tengu Derby (connected blue dots), with the model fitted values (black line) and approximate 95% confidence intervals (gray line). Missing points reflect years when < 5 were caught.

Chart

Description automatically generated

Figure 3. Time series of the mass of the single largest Chinook Salmon caught in the Tengu Derby each year (top), and the number of fish ≥ 5 pounds in light blue and ≥ 10 pounds in dark blue divided by the number of participating anglers each year (bottom).

Chart, histogram

Description automatically generated

Figure 4. Time series of observed Chinook Salmon mass from purse seine fisheries (red) from 1970-2014 and the Tengu derby (blue), including fits from the multivariate random walk model for both time series (dashed lines). Note the shorter period of record compared to Fig. 2.

Chart, line chart

Description automatically generated

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1. This word refers to the practice of getting something without paying, as in sponging or cadging. [↑](#footnote-ref-1)